METHOD OF THE CONTROLLED CURRENT REGULATION – INDUCED POLARIZATION

METODA KONTROLOVANÉ REGULACE PROUDU – VYNUCENÁ POLARIZACE

František Ryšavý [1]

Abstract

This paper returns to the well-logging method named as the controlled current regulation before and later abandoned. Theory of that method is applied to the real focused electric field for the induced polarization. There can be manufactured two variants of equipment; the first registering the static chargeability of rocks and the second being able to record the selective chargeability of rocks. For both above variants there is explained theory of interpretation, too. The suggested procedure evaluation of the method is all new and differs of the old procedure by that goes through partial constants characterizing electrode array. These can be exactly counted what makes possible to calibrate records directly in chargeability.

Abstrakt

Tato práce se vrací ke karotážní metodě pojmenované dříve jako metoda kontrolované regulace proudu, později ale opuštěné. Teorie metody je aplikována na reálné usměrněné elektrické pole používané pro vynucenou polarizaci. Zařízení může pracovat ve dvou variantách: první z nich registruje statickou polarizovatelnost hornin, druhá může registrovat selektivní polarizovatelnost hornin. Pro obě varianty je rovněž vysvětlena teorie interpretace. Navržený postup vyhodnocení této metody je zcela nový a liší se od starého postupu tím, že používá dílčí konstanty, které charakterizují uspořádání elektrod hlubinné sondy. Tyto konstanty je možno přesně spočítat, což s sebou nese, že můžeme kalibrovat karotážní záznamy přímo v polarizovatelnosti prostředí.

Keywords

induced polarization, focused electric field, static chargeability, selective chargeability, well-logging

Klíčová slova

vynucená polarizace, usměrněné elektrické pole, statická polarizovatelnost, selektivní polarizovatelnost, karotáž

1 Introduction

It was MARUŠIAK, I. (1968) and (1969) who had presented that principle of the controlled current regulation based on the electrical focused field for registration of induced polarization. The mentioned principle was wider and had been applied not only for induced polarization, but too, for Laterolog, Microlaterolog and for registration of static and selective SP-potentials.

MARUŠIAK, I. (1968) and (1969) attempted to imply the mentioned method for registering Laterolog. He measured four non-focused resistivity curves that were computerized after the before algorithm. The final curve was compared to the real resistivity curves of Laterolog. However, he was not successful. This was bad result tending to abandonment of computerizing of the final resistivity curve and the method of the controlled current regulation stopped for using.

In spite of that, the principle of the controlled current regulation remains permanently interesting, because its theory makes possible the construction of new equipments having real focusing of the electric field and interpretation of data recorded with this equipment, too. The aim of this paper is application of theory of the controlled current regulation on the method of induced polarization and to resuscitate in new way that old principle implemented in the 60 - s of last century by MARUŠIAK, I. (1968).The well-logging method is suitable for any mud, because simulates virtually replacement of real mud by the absolutely non-conductive mud for each such measurements. It makes possible to register the chargeability tending to the chargeability of non-invaded zone without an influence of the rock resistivity when holds condition $U_N = U_M$

2 Theory of method

Conventional electrode array, theory and interpretation has been in detail described in paper RYŠAVÝ, F. (2012) where are too references to next papers of Czech and foreign geophysicists who investigated the IP-method. The aim of this paper is to imply principles of the method controlled current regulation on induced polarization. It is why I use new electrode array, as well, new theory that is different of that used in RYŠAVÝ, F. (2012).

The basic fact is focusing of electric field simulates a mud replacement. The real mud replacement would be very expensive. The virtual one is very effective. It is possible to simulate either absolutely conductive mud, or absolutely non-conductive. Implication of focusing of electric field is for the chargeability registration important mainly when holds condition $U_N = U_M$. Under this condition it is possible completely to eliminate an influence of mud,

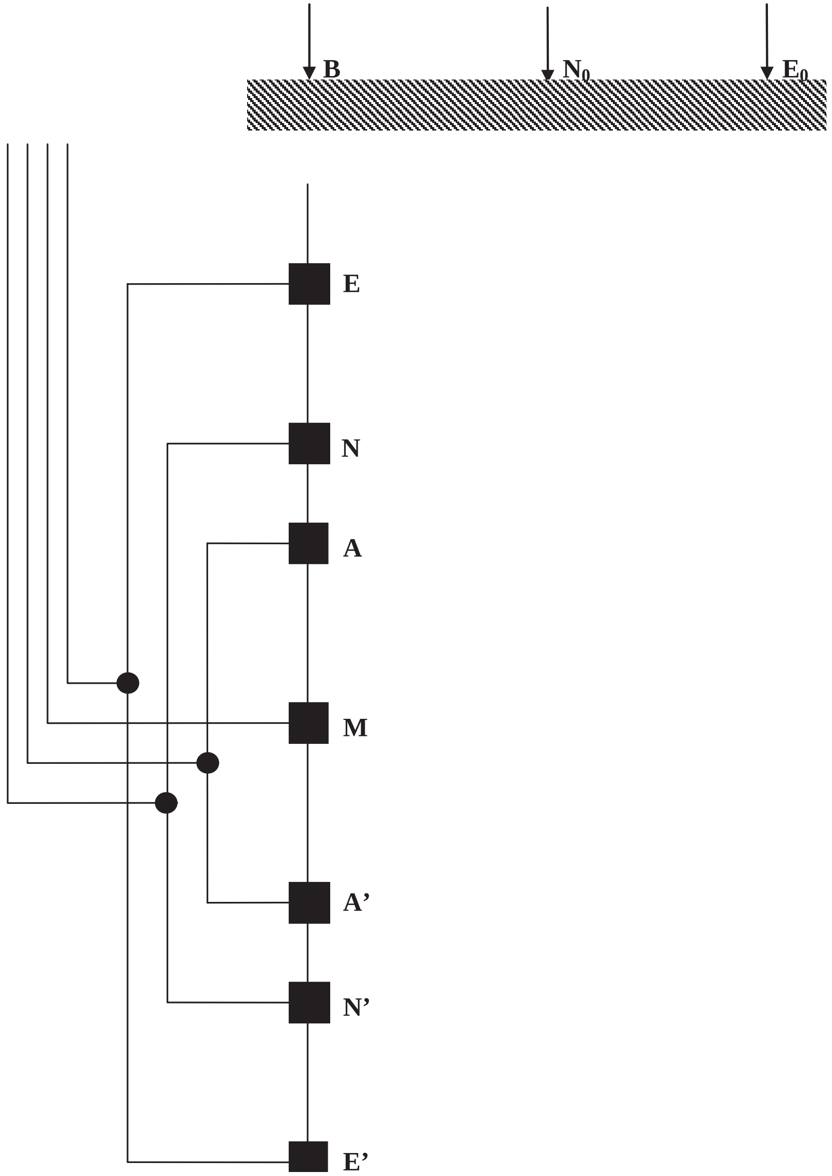

Fig.1 The array of the electrode tool for the method of induced polarization using the principle of the focused electric field; after Marušiak, I. (1968) and (1969)

invasion zone and adjacent beds on measurement of the chargeability for every measurement. The registered chargeability in such case tends to the real chargeability of non-invaded zone non-affected with the resistivity of around environment. It holds for any real mud having any resistivity. Focusing electric field on condition $U_N = U_M$ presents as if you have replaced the real mud with a virtual absolutely non-conductive mud having an infinity resistivity. It holds for each of measurements in boreholes. The current contours enter perpendicularly into the rock wall; from real muds it is close to the mud on oil basis. The well-logging records emphasize the thin layers like are thin coal seams or thin uranium beds deposited in sedimentary rocks. More in chapter 6, formula (33)

The starting point is the array of electrodes presented in fig.1. For the focused electric field it holds that the electric contours going out of current electrodes denoted as A and A', current electrodes, enter into the borehole wall almost perpendicularly. This is provided by the guard electrodes E and E'.

The electrode array is similar to the array of 7-electrode Laterolog. However, here in the centre is not the current electrode A, but potential electrode M. The current electrodes A and A´ are inserted between potential electrodes M, N and M, N´. It is the main difference in comparison to 7-electrode Laterolog. The guard electrodes E and E´ remain again like the outer.

The electric field is a bit different than it is in the case of the 7-electrode Laterolog. The contours of the feeding current I_A flow to electrodes E and E´ where are curved up to such degree that go perpendicularly into the borehole wall, however in the centre around electrode M is a bit other situation. Here the current contours flowing from electrodes A and A´ go against one another. It looks that around electrode M is electric field of the current I_A locally eliminated.

The regulative current I_E flows through mud parallelly to the borehole wall from electrodes E and E´ to electrodes A and A´. There is curved and so goes perpendicularly into the borehole wall. It seems that does not reach the space domain around electrode M. Simply speaking, the final electric field around the before electrode M is diluted. The current contours are either far from one another, or completely are not.

Registration of induced polarization reacts on the current pulse in rocks. The first step is action of the rectangular current pulse on the outer environment. The voltage of such pulses is measurable. Electric current denoted as I_A flowing through A, A' and B electrodes must be stabilized. The second step is the current is cut, i.e., it holds that $I_A = 0$ what means that $I_E = 0$, too. Then you will register the voltage being between electrode M and electrodes N_0 or N; it runs first or second variants. Concurrently it holds that the regulation is made with the help of the regulative current denoted as I_E flowing through E, E' and E_0 electrodes. Its size is directed by either condition that $U_N = U_M$, this is first variant of registration for the static chargeability of rocks, or that $U_N = 0$, it is the second variant for registration of the selective chargeability of rocks. The regulative current I_E acts synchronously with the current I_A that is periodically cut. The regulative current forms the focused electric field and simultaneously keeps conditions of regulation; either $U_N = U_M$ or $U_N = 0$.

Terminology, the static chargeability and the selective chargeability, has created after analogy registering static and selective SP-potentials where identical conditions for the current regulation are. It was the main reason.

3 Registration of the static chargeability of rocks κ_e^{SIP} on condition that $U_N = U_M$

This is first variant of the technical equipment. Voltage creating on electrodes M and N is following:

$$U_M = \kappa_e \times \frac{R \times I_A}{k_{AM}} + \kappa_e \times \frac{R \times I_E}{k_{EM}} \text{, and} \tag{1}$$

$$U_N = \kappa_e \times \frac{R \times I_A}{k_{AN}} + \kappa_e \times \frac{R \times I_E}{k_{EN}} . \tag{2}$$

Both equations can be adjusted on this form:

$$U_M = \kappa_e \times \left(\frac{R \times I_A}{k_{AM}} \right) \times \left[1 + \frac{k_{AM}}{k_{EM}} \times \left(\frac{I_E}{I_A} \right) \right] \text{, and} \tag{3}$$

$$U_N = \kappa_e \times \left(\frac{R \times I_A}{k_{AN}} \right) \times \left[1 + \frac{k_{AN}}{k_{EN}} \times \left(\frac{I_E}{I_A} \right) \right] . \tag{4}$$

Now, it needs to define the coefficient of focusing for the electric field which is denoted as η. This will be positive, $\eta > 0$, as you will have seen later.

$$\eta = \frac{I_E}{I_A} . \tag{5}$$

The regulative current I_E is determined thanks to equation (5):

$$I_E = \eta \times I_A \ . \tag{6}$$

The fundamental condition of regulation for this type of registration is $U_N = U_M$. Equation (6) will be used then in equations (1) and (2) and you attain the next forms of those formulas:

$$U_M = \kappa_e \times (R \times I_A) \times \left[\frac{1}{k_{AM}} + \frac{1}{k_{EM}} \times \eta \right] \text{, and} \tag{7}$$

$$U_N = \kappa_e \times (R \times I_A) \times \left[\frac{1}{k_{AN}} + \frac{1}{k_{EN}} \times \eta \right] . \tag{8}$$

The coefficient of focusing is calculated for condition that it holds $U_N = U_M$. You receive that:

$$\frac{1}{k_{AM}} + \frac{1}{k_{EM}} \times \eta = \frac{1}{k_{AN}} + \frac{1}{k_{EN}} \times \eta . \tag{9}$$

This is that equation needed for calculation of η.

$$\eta = \frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} . \tag{10}$$

For regulative current I_E holds this equation:

$$I_E = \eta \times I_A = \left(\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right) \times I_A . \tag{11}$$

We register voltage being between electrode M in borehole and electrode N_0 on the surface of earth on condition that $U_N = U_M$. The voltage U_M created by polarization is proportional to the voltage of the outer polarizing field denoted as U_{M_0}. At the moment when the outer polarizing field does not affect, i.e. $I_A = 0$, you register the electric field of polarization after formula (12) influenced by before acting the voltage U_{M_0} after formula (13) which had created the just registered field of polarization having voltage U_M. Note, please, that both mentioned voltages are dependent on resistivity of rocks R.

$$U_M = \kappa_e \times U_{M_0} \times \left[1 + \frac{k_{AM}}{k_{EM}} \times \eta \right] \text{, and} \tag{12}$$

$$U_{M_0} = \frac{R \times I_A}{k_{AM}} , \tag{13}$$

where U_{M_0} = the voltage of the outer polarizing field [mV], and

U_M = the voltage created due to the polarization field [mV].

The current denoted as I_A must be stabilized. The static chargeability of rocks denoted as κ_e^{SIP} is defined as follows:

$$\kappa_e^{SIP} = \frac{U_M}{U_{M_0}} . \tag{14}$$

The characteristic κ_e^{SIP} is dimensionless. Owing to formula (14) there is all eliminated influence of resistivity of rocks. Now, we shall use formula (12) which must be adjusted and its form is like this:

$$\kappa_e^{SIP} = \kappa_e \times \left[1 + \frac{k_{AM}}{k_{EM}} \times \eta \right] . \tag{15}$$

You can use the next substitution and attain the very important constant being denoted as K_{SIP}:

$$K_{SIP} = 1 + \frac{k_{AM}}{k_{EM}} \times \eta = 1 + \left(\frac{k_{EM}^{-1}}{k_{AM}^{-1}} \right) \times \left(\frac{k_{AN}^{-1} - k_{AM}^{-1}}{k_{EM}^{-1} - k_{EN}^{-1}} \right) . \tag{16}$$

Relation (15) tends to the final adjustment:

$$\kappa_e^{SIP} = K_{SIP} \times \kappa_e \ , \tag{17}$$

where κ_e^{SIP} = the static chargeability of rocks,
κ_e = the real chargeability of rocks, and
K_{SIP} = the dimensionless constant of the electrode tool.

The characteristic κ_e^{SIP} can be registered directly, because you can calibrate chargeability with the help of ratio of two voltages. It is an apparent factor that is registered. Thanks to formula (17) you can very fast determine the real chargeability. Constant K_{SIP} is dimensionless in comparison to partial constants being dimensional in [m]. The constants K_{SIP} and η can be exactly enumerated and because the current I_A is registered, it presents that the size of the regulative current I_E is exactly enumerated, as well. The static chargeability registers the borehole section in details; the very thin beds are well visible.

4 Registration of the selective chargeability of rocks κ_e^{SLIP} on condition that $U_N = 0$

This is the second variant of the technical equipment. We have again to use equations (3) and (4) for U_M and U_N. Both equations can be adjusted like this:

$$U_M = \kappa_e \times \left(\frac{R \times I_A}{k_{AM}} \right) \times \left[1 + \frac{k_{AM}}{k_{EM}} \times \eta \right] \text{, and} \tag{18}$$

$$U_N = \kappa_e \times \left(\frac{R \times I_A}{k_{AN}} \right) \times \left[1 + \frac{k_{AN}}{k_{EN}} \times \eta \right] . \tag{19}$$

The condition of regulation for this variant is that $U_N = 0$. Thanks to the mentioned condition you will obtain relation:

$$1 + \frac{k_{AN}}{k_{EN}} \times \eta = 0 . \tag{20}$$

This is that fundamental equation for calculation of η. The coefficient of focusing is then following:

$$\eta = - \frac{k_{EN}}{k_{AN}} \ . \tag{21}$$

This coefficient is negative, i.e., it holds that $\eta < 0$. Because it holds that $\eta < 0$ the regulative current I_E will be negative too. The current I_E flows in opposite direction than it is for the current I_A. It is possible to write:

$$I_E = \ - I_A \times \eta = - \left(\frac{k_{EN}}{k_{AN}} \right) \times I_A . \tag{22}$$

This relation results from equation (5). In this variant you shall register, too, the voltage U_M after formula (18); however, it is the voltage difference being between electrodes M and N on condition that $U_N = 0$.

$$U_M = \kappa_e \times U_{M_0} \times \left[1 + \frac{k_{AM}}{k_{EM}} \times \eta \right], \text{ and} \tag{23}$$

$$U_{M_0} = \frac{R \times I_A}{k_{AM}}. \tag{24}$$

Thus, you will get formulas denoted as (25) and (26). Here is again eliminated influence of resistivity of rocks.

$$\kappa_e^{SLIP} = \frac{U_M}{U_{M_0}} = K_{SLIP} \times \kappa_e \text{ , and} \tag{25}$$

$$K_{SLIP} = 1 + \frac{k_{AM}}{k_{EM}} \times \eta = 1 - \left(\frac{k_{EM}^{-1}}{k_{AM}^{-1}} \right) \times \left(\frac{k_{AN}^{-1}}{k_{EN}^{-1}} \right) \text{ ...for } K_{SLIP} > 0. \tag{26}$$

where κ_e^{SLIP} = the selective chargeability of rocks,
κ_e = the real chargeability of rocks,
K_{SLIP} = the dimensionless constant of the electrode tool,
U_{M_0} = the voltage of the outer polarizing field [mV], and
U_M = the voltage created due to the polarization field [mV].

At formula (26) we shall do a short stop. You noted that equation follows condition that $K_{SLIP} > 0$. It is difficult to conceive that the constant of the electrode tool is negative. However, mathematically, it can be. All partial constants k_{AM} , k_{AN}, k_{EM} and k_{EN} must be only positive. If they are not, it will be certainly an error. Algorithm of counting for K_{SLIP} says that generally hold $K_{SLIP} < 0$, too. It is about that a certain electrode array of tool admits negative constant. It can be an outer expression of some hidden phenomenon which can be real. Unfortunately, I did not find explanation what it was and why it can be. Therefore I implied condition $K_{SLIP} > 0$ and all negative values I exclude. This consideration holds generally for all method of the controlled current regulation.

Electric field formed with the current contours of I_A is wide, because electrodes A, A´ and E, E´ all have the same charge. The contours go perpendicularly into the borehole wall. Electric field of the regulative current I_E is other. The current contours go out from E and E´ and flow by mud to electrodes A and A´, that curve them up to such degree they go perpendicularly into the borehole wall. They have the same direction like those belonging to current I_A. The coefficient of focusing is positive. In case that the coefficient is negative, the contours of I_E go against those of I_A. They extend from the borehole wall toward electrodes A and A´. Then they are curved and flow through mud to both guard electrodes E and E´. Of course, both electric fields superpose and the result is final electric field. Maybe, somewhere here can be explanation why the constant of tool denoted as K_{SLIP} is negative.

The coefficient of focusing η will be different in comparison to the former one for κ_e^{SIP}. That presents we have various constant K which is dimensionless and the regulative current I_E is different too. We register voltage difference being between electrode M and electrode N, both are in the borehole, on condition that $U_N = 0$. This the main difference to the first variant of registration.

5 General information describing constants denoted as k_{AM}, k_{EM}, k_{AN} and k_{EN}

These constants determine factors of higher degree like are: the constant K_{SIP}/ K_{SLIP} and the coefficient of focusing η. Both above factors affect calculation of the chargeability κ_e^{SIP}, κ_e^{SLIP} and, too, the regulative current I_E. The lower constants are dependent on geometry, i.e., on distance being between centres of the current and potential electrodes, denoted as spacing, and on the form and dimensions of electrodes, as well. For the method of induced polarization the surface of electrodes is a mantle of cylinder. Calculation is made due to multiple integration of contribution of the point current source being on the surface of electrodes. This is theme having been published earlier, RYŠAVÝ, F. (2013). As you see **in fig.1 current and potential electrodes are not identical**, that is why there are valid these formulas:

$$\left(\frac{k}{a_L}\right) = \frac{1}{F_1 + F_2}, \tag{27}$$

$$F_1 = \frac{1}{8} \times \left(\frac{n}{a_n}\right)^{-1} \times \left\{ \ln\left[\left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{2L}{a_L} + \frac{m}{a_m}\right)^2 + 1} + \frac{n}{a_n}\right] - \ln\left[\left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{2L}{a_L} + \frac{m}{a_m}\right)^2 + 1} - \frac{n}{a_n}\right]\right\}, \tag{28}$$

$$F_2 = \frac{1}{16} \times \left(\frac{n}{a_n}\right)^{-1} \times \left\{ \mathrm{Argsinh}\left[\left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{2L}{a_L} + \frac{m}{a_m}\right)^2 + 1} + \frac{n}{a_n}\right] - \mathrm{Argsinh}\left[\left(\frac{\sqrt{2}}{2}\right) \times \sqrt{\left(\frac{2L}{a_L} + \frac{m}{a_m}\right)^2 + 1} - \frac{n}{a_n}\right]\right\} \tag{29}$$

where L = distance being between both centres of the current and potential electrodes [m],
m = length of the current electrode [m],
n = length of the potential electrode [m],
a_L = diameter of the tool body [m],
a_m = diameter of the current electrode [m], and
a_n = diameter of the potential electrode [m].

The above formulas are used for counting of partial constants denoted as k_{AM} , k_{AN}, k_{EM} and k_{EN}. They can be very exactly counted. For other electrode array when **the current and potential electrodes are identical** you can use formulas defined in RYŠAVÝ, F. (2013) solving such partial electrodes.

What is further very important is implementing of segmented electrodes to exclude an influence of electrode potentials creating when the surface of metallic electrode comes in contact with mud. For segmented electrodes of cylindrical type you can use this formula:

$$\left(\frac{k}{a_L}\right) = \frac{1}{n} \times \sum_{i=1}^{n} \frac{1}{F_{1i} + F_{2i}} = \frac{1}{n} \times \sum_{i=1}^{n} \left(\frac{k}{a_L}\right)_i \quad , \qquad (30)$$

The formula is from paper RYŠAVÝ, F. (2006) where are described different type segmented electrodes and explained principles their activity.

6 Discussion over focusing of electric field

You noticed too that favourable condition is when $U_N = U_M$, whereas, when holds that $U_N = 0$ it is less favourable condition. In both cases you have electric field that is focused, however, variants of focusing are different. In the first variant the current contours are perpendicular to the borehole axis and go perpendicularly into the borehole wall. They penetrate deeply inwards rocks and in big distance from the wall they are curved and return to electrode B. The second variant offers too focused electric field. The current contours go too into rocks but because are intensively curved at once from start in the direction being parallel to the borehole axis, they stretch mainly invasion zone and mud.

We can study both variants more in detail. I utilize from work, SCHLUMBERGER (1989) that formula where the published relation between pseudo-static and static SP-potentials is. It seems you can use very similar one for the induced polarization.

$$U_M = \kappa_e^{(t)} \times U_{M_0} \times \frac{\kappa_e^{(m)} \times R_m}{\kappa_e^{(m)} \times R_m + \kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t} \ . \qquad (31)$$

This formula can be adjusted in the way like that:

$$\kappa_e^{*} = \frac{U_M}{U_{M_0}} = \kappa_e^{(t)} \times \frac{\kappa_e^{(m)} \times R_m}{\kappa_e^{(m)} \times R_m + \kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t} \ , \qquad (32)$$

where R_m = the mud resistivity [Ωm],
R_s = the resistivity of adjacent beds [Ωm],
R_i = the resistivity of invasion zone [Ωm], and
R_t = the resistivity of non-invaded bed [Ωm].

Now, we are able to simulate virtually the non-conductive mud column having infinite resistivity, i.e., $R_m \to \infty$. This condition is important because makes possible all to eliminate an influence of mud, invasion zone and adjacent beds on measurement of the real chargeability of non-invaded zone non-affected with the resistivity of the around environment. It holds for any mud having any resistivity. It can be with the help of the electrode array and focusing electric field always made. It is technical thing. Equation (32) will gain the following form:

$$\kappa_e^{SIP} = \frac{U_M}{U_{M_0}} = \lim\nolimits_{R_m \to \infty} \kappa_e^{(t)} \times \frac{1}{1 + \left(\dfrac{\kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t}{\kappa_e^{(m)} \times R_m} \right)} \approx \kappa_e^{(t)}, \quad \text{for } U_N = U_M. \tag{33}$$

In this case we are possible to create non-conductive mud column with the help of electric field focusing, even if the real mud column is various sometimes highly conductive. The result is that the static IP is independent on the around resistivity and because the current contours go deeply inwards rocks, the registered static chargeability is close to **the real chargeability of non-invaded zone**.

We can analyse too the second variant. It is possible to simulate virtually the absolutely conductive mud column having zero resistivity, i.e., $R_m \to 0$. It holds again for any mud having any resistivity. The condition $U_N = 0$ means the electric current contours flow parallelly to the borehole axis. It is as if you replaced the real mud with very salt water. It is the second case; equation will have definition like this:

$$\kappa_e^{SLIP} = \frac{U_M}{U_{M_0}} = \lim\nolimits_{R_m \to 0} \kappa_e^{(t)} \times \frac{1}{1 + \left(\dfrac{\kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t}{\kappa_e^{(m)} \times R_m} \right)} \approx \kappa_e^{(t)} \times \left(\frac{\kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t}{\kappa_e^{(m)} \times R_m} \right)^{-1} \approx$$

$$\approx \kappa_e^{(t)} \times \frac{\kappa_e^{(m)} \times R_m}{\kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i + \kappa_e^{(t)} \times R_t} \approx \kappa_e^{(t)} \times \frac{\left(\dfrac{\kappa_e^{(m)} \times R_m}{\kappa_e^{(t)} \times R_t} \right)}{1 + \left(\dfrac{\kappa_e^{(s)} \times R_s + \kappa_e^{(i)} \times R_i}{\kappa_e^{(t)} \times R_t} \right)} \approx \kappa_e^{(t)} \times \left(\frac{\kappa_e^{(m)} \times R_m}{\kappa_e^{(t)} \times R_t} \right) \approx \kappa_e^{(m)} \times \left(\frac{R_m}{R_t} \right), \tag{34}$$

if holds that $R_t \to \infty$ and for $U_N = 0$.

This event shows that when the current contours are focused parallelly to the borehole axis, the registered chargeability is close to **the real chargeability of mud** to top it all influenced by resistivities of rock and mud. An invasion zone, adjacent beds and mud, too, affect strongly the chargeability because penetration of electric field inwards a rock is smaller. Note please too, that the beds having high resistivity when $R_t >> R_m$ achieve completely to erase the real chargeability of rock almost to zero. Most they are the beds with thin thickness and very high resistivity. It is evident that the static chargeability is much more important than the selective chargeability. That is why you can expect that the second variant will not be too used.

7 Calibration of the induced polarization method

In Czech Republic calibration of IP was successfully solved in 70-s by KŘESŤAN, J. (1974). He made concrete standard assembled from passive electronic elements after the electric model of environment. Standardization of measurements was done by comparison of the single well-logging records with this basic standard.

The way of calibration which is here described is other. In the last years I was presented at metrological training in Ufa, Russia. Very important part of this training was calibration of all dimensional and dimensionless characteristics recorded in well-logging. Participants of training had possibility to study from manuals used in Metrological Institute for Oil Well-Logging in Ufa. Chargeability, in the same manner as all dimensionless characteristics, was calibrated with the help of ratio between two voltages. I ascertained this way like simple, credible and easy available. It was why I used this way of calibration in this chapter.

For calibration you need to have a calibrator being the part of equipment. The chargeability of rocks is defined as the ratio of two voltages. In accordance to formulas (14) and (25) it is:

$$\frac{U_M}{U_{M_0}}. \tag{35}$$

The calibrator consists of two independent voltage sources having accurately calibrated their values in [mV]. The output of calibrator presents the voltage ratio (U_1/ U_2) simulating a chargeability. This ratio presents the standard-signal for calibration. If we use a linear scale, one ratio as standard of the chargeability is enough; however, for non-linear scale you will need to have all set of such standards. Now we can define a standard of the simulated apparent chargeability that is related to the concrete electrode array:

$$\kappa_0 = \frac{U_1}{U_2} \times K = \kappa_e \times K \text{ , } K = K_{SIP} \cup K_{SLIP} \text{ .} \tag{36}$$

As both voltages are determined with certain accuracy the simulated chargeability denoted as κ_0 will have its accuracy too. In so way it is possible to determine the error of calibration. Deflection denoted as l_0 answering to κ_0 you get after this formula:

$$l_0 = \frac{\kappa_0}{n}, \tag{37}$$

where n = the step of linear scale [κ / 1cm], and

l_0 = deflection reflecting value of etalon [cm].

Verification of the voltage ratio (U_1/ U_2) goes through the control of both voltages U_1 and U_2 . These have their exact values and the confidence interval. The control you made with highly precise gauge. The resulting value must be inside of the confidence interval.

The next important step is verification of all equipment including the electrode tool too. Verification is made in the test pit having fresh water and being of big radius enough. The fresh water presents the secondary etalon of the chargeability. This etalon is derived from the primary etalon of calibrator. Due to registrations by both electrode tools we are able to specify the confidence interval of the allowed deflections in fresh water. The water environment allows to control stability of the above interval within time and to determine new value with the help of the primary etalon of calibrator. Then, if the equipment is well-adjusted, deflections in fresh water will be in the confidence interval of allowed deflections.

8 Conclusions

The principle of the controlled current regulation based on existence of the real focused electric field enables us to register the chargeability of rocks by the method of induced polarization. Registration can be made with two ways presenting each of them a bit various electric circuit after condition of regulation. Theory made by MARUŠIAK, I. (1968) and (1969) holds as well, nevertheless, a certain adjustment had to be made. Here are conclusions resulting from the former analysis:

- The technical construction presents two different circuits of the same equipment. Either we register the static chargeability of rocks with the help of condition that $U_N = U_M$, or we register the selective chargeability of rocks when it holds that $U_N = 0$.
- Both variants have factors like the constant of the electrode tool K and the coefficient of focusing η. Both factors are dimensionless.
- Both factors K and η are formed by partial constants of lower degree denoted as k_{AM}, k_{EM}, k_{AN} and k_{EN}. They depend on geometry given by electrode spacing and dimensions of electrodes.
- The size and direction of flowing of the regulative current I_E is determined by factor η. The above current is periodically cut like it is for the feeding current I_A.
- The depicted tool after MARUŠIAK, I. is not the only tool for registering method of induced polarization. You can use, for example, the tool having 9 electrodes like it is at authors GUOZHU, N. and HUI, X. (2009) who used such tool for recording the static and selective SP-potentials. And the same 9-electrode tool can be used for recording of Laterolog. The mode of measurement is for each of methods characteristic and different one another.

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Author

[1] RNDr. František Ryšavý, Lesní 3, 695 03 Hodonín, Czech Republic, rysavy.frantisek@seznam.cz